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Non-thermal particles in the intergalactic and intracluster medium

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Abstract. I present a review of nonthermal processes in the large scale structure of the universe. After examining the properties of cosmological shock waves and their role as particle accelerators, I discuss the main observational facts, from radio to γ-ray and describe the processes that are thought be responsible for the observed nonthermal emissions. Finally, I emphasize the important role of γ-ray astronomy for the progress in the field. Non detections (upper limits) at these photon energies have already allowed us to draw important conclusions. Future observations will tell us more about the physical conditions in the intracluster medium, physics of shocks dissipation, aspects of CR acceleration.

Key words. acceleration of particles — cosmology: large-scale structure of universe — galaxies: clusters: general — gamma rays: theory — radiation mechanism: non-thermal — shock waves

1. Introduction

The existence of extended regions populated by cosmic ray electrons (CRes) in at least some clusters of galaxies has been apparent since the discovery of diffuse, non-thermal radio emissions from the Perseus and Coma clusters more than thirty years ago (Leslie & Elsmore 1961; Willson 1970). Their importance as indicators of physical processes in the cluster media has grown in recent years as the number of detected diffuse radio emission clusters has increased, as reports have appeared of possible diffuse non-thermal emissions in the hard X-ray (HXR) and extreme ultraviolet (EUV) bands (e.g. Lieu et al. 1996; Fusco-Femiano et al. 1999) and as the evidence has mounted for a rich variety of highly energetic phenomena in and around clusters that seem capable of energizing the electrons. Still, today, the origin of cluster CRes is not clear, although many proposals have been made.

2. Cosmic Shock Waves

An early study of cosmic shocks was carried out in Sunyaev & Zel'dovich (1972) who studied the evolution of individual perturbation modes till their nonlinear breakup, and Bertschinger (1985) who worked out self similar models describing the development of infall flows in an Einstein-de Sitter universe. Miniati et al. (2000) have carried out a detailed study of cosmic shocks based on numerical simulations of structure formation. Their analysis was aimed at establishing the statistical properties of cosmic

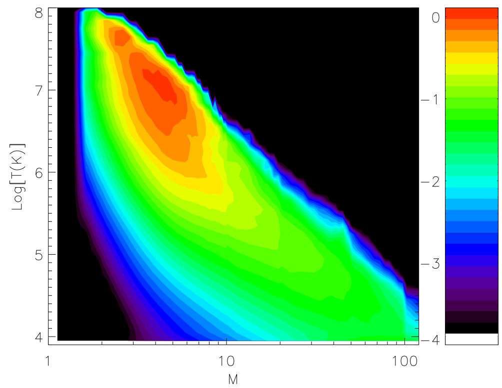

Fig. 1. Top: Two dimensional diagram showing the differential of the thermal energy per unit log interval in both Mach number and temperature produced at cosmic shocks throughout cosmic history. It is shown in units of keV per particle.

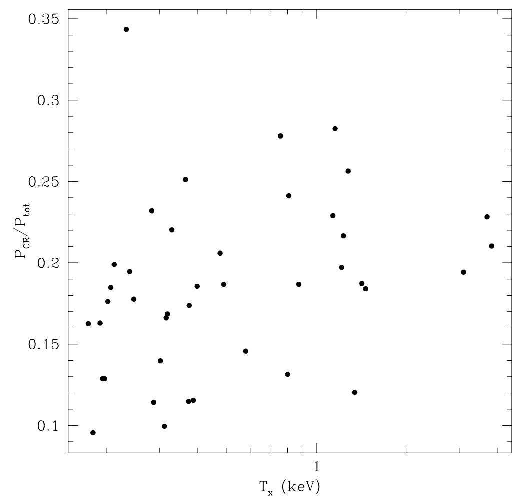

Fig. 2. Ratio of CR to thermal pressure averaged over the group/cluster volume within 1.0 h^{-1} Mpc plotted as a function of group/cluster core temperature.

shocks in view of their potential role as high energy particle accelerators. In fact, astrophysical shocks are collisionless and as part of the dissipation process generate, a supra-thermal distribution of high energy particles, namely cosmic-rays (CR). Thus Miniati et al. (2000) for the first time plotted the distribution of shocks as a function of Mach number. This is important to know for assessing the potential conversion of the shocks kinetic energy (more precisely, ram pressure) into cosmic-rays. In Fig. 1 provides an example of such a diagram showing, as a function of pre-shock temperature, T_1, and shock Mach number, M, the thermal energy per unit log M and T_1 dissipated at cosmic shocks throughout cosmic history ($\partial^2 \Delta E_{th}/\partial \log M \partial \log T_1$ Miniati 2002). The structure of the accretion shocks was found highly complex, irreducibly three dimensional and well beyond the capability of analytic description (Miniati et al. 2000). Another important result, relevant for shock acceleration (see below), was that a significant fraction of the shock energy is dissipated in relatively strong, high Mach number shocks (Miniati et al. 2000; Miniati 2002). The recent resolution study of Ryu et al. (2003) confirms this earlier main findings of Miniati et al. (2000). They showed that as higher resolution is employed, weaker shocks become more numerous, although the strong shocks remain unaffected. The highest resolution simulation, with the same resolution as Miniati (2002) but twice as large a box, was characterised by a peak of the distribution plotted in Fig. 1 at slightly lower values than Miniati (2002). While this does not affect the shocks mainly responsible for the high energy CRs, it is likely that most of the "extra" weak shocks in Ryu et al. are not even associated with virialized structures (Ryu et al. 2003).

3. Cosmic-ray Pressure

Miniati et al. (2001b) studied the production of CR protons at cosmic shocks by carrying out a numerical simulation of structure formation that included *directly* shock acceleration (in the test-particle limit approximation), transport and energy losses

of the CRs (Miniati 2001). CR injection takes place at shocks according to the thermal leakage prescription, leading to the injection, as CRs, of a fraction about 10^{-4} of the thermal protons passing through a shock. According to those results, cosmic ray ions may provide a significant fraction of the total pressure in the intracluster medium (Fig. 2). This is basically because: (i) intergalactic shocks are characterized by relatively large Mach numbers (Miniati et al. 2000; Miniati 2002); (ii) relativistic protons in the diffuse ICM are only mildly affected by energy losses and (iii) up to energies $\sim 10^{15}$ eV are basically confined within Mpc scales (Völk et al. 1996) by μG turbulent magnetic fields (Clarke et al. 2001). However, such conclusion cannot be made strictly quantitative yet, primarily because it depends on the unknown CR injection/acceleration efficiency at shocks. Although a number of indirect argument can be made in order to constrain the CR content in the ICM, such as radio emission from secondaries (Blasi & Colafrancesco 1999; Miniati et al. 2001a; Miniati 2003), the best observational assessments will be possible through γ-ray emission (see below). In principle, though, CR pressure could account up to a few tens of percents of the total ICM pressure. The cosmological consequences of this result were discussed in Miniati et al. (2001a).

4. Radio Emission

About 30% of massive galaxy clusters (GC) exhibit diffuse radio synchrotron emission extending over Mpc scales (Feretti, these proceedings). Two broad classes have been identified. *Radio halos* have a regular morphology resembling that of the thermal X-ray emission and no sign of polarization, whereas *radio relics* are elongated, located at the periphery of a cluster, and exhibit polarized emission (Feretti, these proceedings). The short cooling time of the emitting CR electrons and the large extension of the observed radio sources seem to require

Fig. 3. Diffuse synchrotron radio emission produced by shock accelerated electrons.

ongoing acceleration mechanism in the intracluster medium (ICM).

4.1. Radio Halos

Radio halos are usually found in rich clusters with high ICM temperature, $T \gtrsim 7$keV, and high X-ray luminosity, $L_x(0.1-2.4\text{keV}) \gtrsim 5\times10^{44}\text{erg s}^{-1}$ (Feretti, these proceedings). Since it usually extends over a linear size of about 1 h^{-1}Mpc, the radio emission appears to be a characteristic of the whole cluster, rather than being associated with any of the individual cluster galaxies (Willson 1970). Signatures of a merging process in these clusters are often emphasized and the absence of cooling flows cited as demonstrating the connection between radio halos and mergers (e.g. Buote 2001). However, Liang et al. (2000) (also Bacchi et al. 2003) found a tight and steep correlation between the radio power emitted at 1.4 GHz and the cluster temperature, and suggested that the apparent rarity of detections should be attributed to observational insensitivity to any but the most massive clusters.

A number of ideas have been proposed to explain the origin of the relativistic electrons. It was soon realized that relativistic electrons “ejected” from cluster galaxies during a putative active phase would *not* be able to reproduce the observed radio emission profile (of Coma cluster; Jaffe 1977; Rephaeli 1977). Alternative models commonly assume a continual energization of the relativistic electrons by *in situ* first or second order Fermi processes.

Direct numerical simulations, however, show that shock accelerated electrons produce radio maps where the emission has an irregular morphology and is mostly concentrated in the outer regions (see Fig. 3; Miniati et al. 2001a). That is because in large virialized objects strong shocks occur at the outskirts. In any case this result rules

out shock acceleration mechanism for the origin of radio halos.

The radio electrons could also be produced as secondary products of inelastic p-p collisions of CR ions and the thermal intra-cluster nuclei (Dennison 1980; Vestrand 1982; Blasi & Colafrancesco 1999; Miniati et al. 2001a; Pfrommer & Enßlin 2004). Miniati et al. (2001a) computed self-consistently the population of both shock accelerated CR protons and the secondary $e^{\pm}$ they produce in a simulation of structure formation and found that basically all general properties of radio halos (morphology, polarization, L_{radio} vs T_x relation) where properly reproduced. However, they did predict a spectral steepening of the radio emission. Yet, this does not exclude additional processes, such as the interaction with weak and/or strong ICM turbulence, that would alter the CR protons distribution so as to produce steepening features in the radio spectrum of the secondary $e^{\pm}$. Additional arguments that disfavor secondary models have been put forth by Brunetti (2002) although these have been recently disputed by Pfrommer & Enßlin (2004). In any case, the spectral steepening of Coma radio emission led Schlickeiser et al. (1987) to consider in detail second order Fermi models where the particles are accelerated via their interactions with plasma waves generated by turbulence in the medium. These models are in general more flexible in that a number of free parameters in the transport equation of the CR electrons allows easier fit to the observations. There are, certainly, other more complex physical issues regarding the evolution of the turbulent spectrum, the generation of suitable waves for the acceleration process to properly work, the possible back reaction of the particles on the waves. For example, very recently Brunetti et al. (2003) pointed out that the presence of CR protons bearing just a few per cent of the ICM thermal pressure would damp most of the Alfvèn waves, thus inhibiting turbulent acceleration of CR electrons. The most serious concern for Fermi-II mechanisms is due to their inefficiency at accelerating the particles directly from the thermal pool, a fact that was realized early on (Jaffe 1977). It is usually assumed, often rather casually, that the seed particles are created at shock during merger events. Clearly modeling the CR particles in the ICM is more complex that initially anticipated and requires a combination of several processes including shock acceleration and turbulent reacceleration at some level. It is not clear, though, what type of shock acceleration efficiencies are needed, both for of CR electrons and protons; if those requirements would lead to an overall consistent picture, that is if all other general properties of radio halos would be properly reproduced. These issues will need to be addressed in the future.

4.2. Radio Relics

Clusters hosting radio relics are somewhat less massive and cooler than those related to radio halos. They show no apparent correlation with merger events, are observed in clusters containing cooling flows (Bagchi et al. 1998) and are found both near the cores of clusters and at their outskirts. The spectra are typically steep, but explicit cutoffs are relatively rare even though the cooling time of the relativistic electrons is much shorter than the age of the cluster.

The most likely mechanism for the origin of radio relic emission is acceleration at accretion/merger shocks (Enßlin et al. 1998; Miniati et al. 2001a). In this respect, Roettiger et al. (1999) carried out simulation of binary merger and showed that, as the main large scale shocks propagate out of the merging clusters, two post-shock arcs form which closely resemble the famous radio emission of A3667. Miniati et al. (2001a) computed the evolution of shock accelerated CR electrons in a simulation of structure formation reproducing the main properties of radio emission,

including radio power, morphology, polarization and spectral index.

Some of the peripheral radio emission, particularly those highly filamentary and extending over a few hundred kpc, could be produced by an alternative mechanism, whereby relic relativistic plasma previously injected by radio galaxies, is being reenergized by the passage of an accretion/merger shock (Enßlin & Gopal-Krisna 2001).

5. EUV and HXR excesses

In addition to radio emission, a number of clusters show emission at extreme ultraviolet (e.g. Lieu et al. 1996) and hard x-rays (e.g. Fusco-Femiano et al. 1999) in excess of what expected from the thermal emission of the ICM. Some of the physical implications associated with these measurements were addressed in Miniati et al. (e.g. 2001a). Both measurements are extremely challenging and at the limit of the instrumental capabilities. In fact, the observational results concerning the EUV emission are still debated. Recently questions have also been raised about the existence of HXR emission from Coma cluster (Rossetti & Molendi 2004), although Fusco-Femiano et al. (2004) confirm it.

6. γ-ray Emission

γ-ray observations of galaxy clusters are relevant for a number of reasons. They may provide direct evidence for the existence of CR protons in the ICM, which is important in order to determine the level of CR pressure there and whether or not secondary $e^{\pm}$ are viable models for radio halos. In addition, inverse Compton emission from shock accelerated electrons is of great interest to determine the contribution of this process to the γ-ray background and also to image and possibly investigate accretion shock physics (Miniati 2003). An important point is that, with conservative assumptions about the efficiency of acceleration of CR protons and electrons at cosmic shocks, γ-ray fluxes due to IC and π^0-decay for a Coma-like cluster are expected to be comparable (see Fig. 5; Miniati 2003). In order for the observational results to be properly interpreted, one should be able to discriminate between the two components. As shown below, this should be possible for a nearby clusters, like Coma.

In the following I examine spectral and spatial properties of γ-ray radiation between 10 keV and 10 TeV due to shock accelerated CRs in GCs. The relevant emission processes are: π^0-decay and IC emission from both shock accelerated (primary) CR electrons and secondary $e^{\pm}$ (non-thermal bremsstrahlung turns out unimportant). The left panel in Fig. 4 shows a synthetic map of the integrated photon flux above 100 MeV for a Coma like cluster of galaxies (Miniati 2003).

Because of severe energy losses, γ-ray emitting primary electrons are only found in the vicinity of strong shocks where they are accelerated. Thus, the IC emission they produce is extended and reveals a rich morphology reflecting the complex "web" of accretion shocks surrounding GCs (Miniati et al. 2000). On the other hand, the emission from π^0-decay and $e^{\pm}$ is confined to the cluster core where it creates a diffuse halo which rapidly fades with distance from the center. In fact, $e^{\pm}$ and π^0 are produced at the highest rate in the densest regions where both the parent CR ions and target nuclei are most numerous.

These findings are further illustrated in the right panel of the same figure where synthetic spectra extracted from a core (top; with a 0.5^o radius) and an outskirts region (bottom; a ring with inner and outer radii of 0.5^o and 1.5^o respectively) are shown. As illustrated, the emitted radiation in the outskirts region is strongly dominated by IC emission from primary e^-. Conversely, in the core region π^0-decay (solid thin line) dominates at high photon energy ($>$ 100 MeV) (top panel). Notice that, given the observed radio flux for Coma cluster, if the assumption is made that the radio emission is produced by secondary $e^{\pm}$, the total

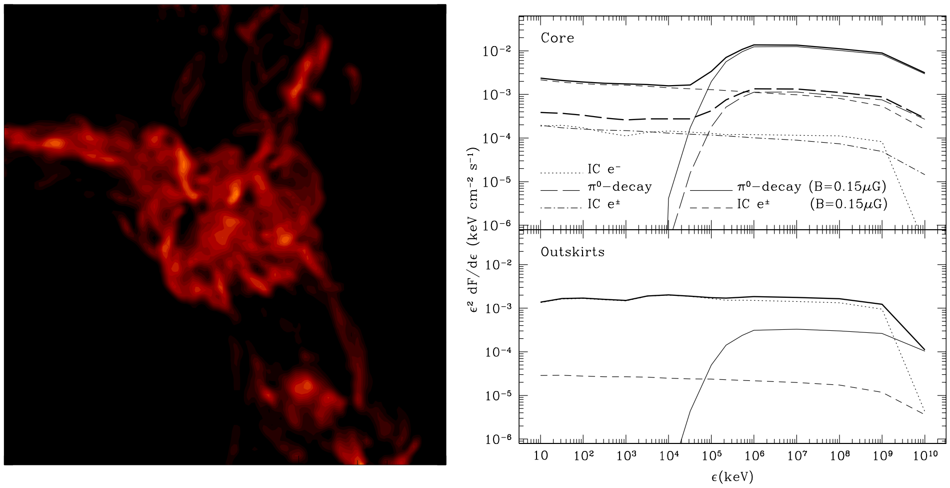

Fig. 4. *Left*: Synthetic map, 15 h^{-1} Mpc on a side, of the integrated photon flux ranging from several $\times 10^{-9}$ to 10^{-11} in units "ph cm^{-2} s^{-1} arcmin^{-2}". *Right*: synthetic spectra extracted from the inner region (top) and the outer region((bottom).

number of protons and of e$^{\pm}$ depends on the magnetic field strength, B. Thus, two cases for $\langle B \rangle$, namely 0.15 and 0.5 μG, are presented in the left panel of fig. 4. Both flux level from the inner and outskirts regions is above the sensitivity limit of upcoming γ-ray facilities, particularly GLAST and also Cherenkov telescopes (MAGIC, HESS, VERITAS, 5@5; Miniati 2003). One delicate issue will concern the performance of these telescope in the observation of extended sources, particularly for Cherenkov telescopes which have a relatively small field of view. Interestingly, the case for detection of γ-ray emission from GCs has already been made in a number of cases (Scharf & Mukherjee 2002; Pfrommer & Enßlin 2003; Iyudin et al. 2004) although future experiments are strongly needed (Reimer et al. 2003).

7. Cosmic γ-ray Background

CR in the large scale structure may contribute a relevant fraction of the cosmic γ-ray background (CBG; Sreekumar et al. 1998). Although recently reassessed to half it initial value (Strong et al. 2003), much of the CGB is still unaccounted for (Chiang & Mukherjee 1998). Decay of neutral π-mesons can realistically produce only a few percent of the measured CGB (Dar & Shaviv 1995; Colafrancesco & Blasi 1998); however, IC emission from electrons accelerated at intergalactic shocks is potentially more promising (Loeb & Waxman 2000).

Fig. 5 (left) shows the contribution to the CGB from CRs accelerated at cosmic shocks according to a simulation of structure formation that included the evolution of CR protons, electrons and secondary e$^{\pm}$. EGRET observational data (solid dots) (Sreekumar et al. 1998) are also shown for comparison. Included are: IC emission of CR electrons scattering off cosmic microwave background photons (dot line), decay of neutral pions produced in p-p inelastic collisions (dash line) and IC emission from secondary e$^{\pm}$ (dot-dash line). In Fig. 5, the total flux (solid line) corresponds roughly to a constant value at the level of 0.2 keV cm^{-2} s^{-1} sr^{-1} throughout the spectrum. It is dominated by IC emission from primary electrons. Fractions

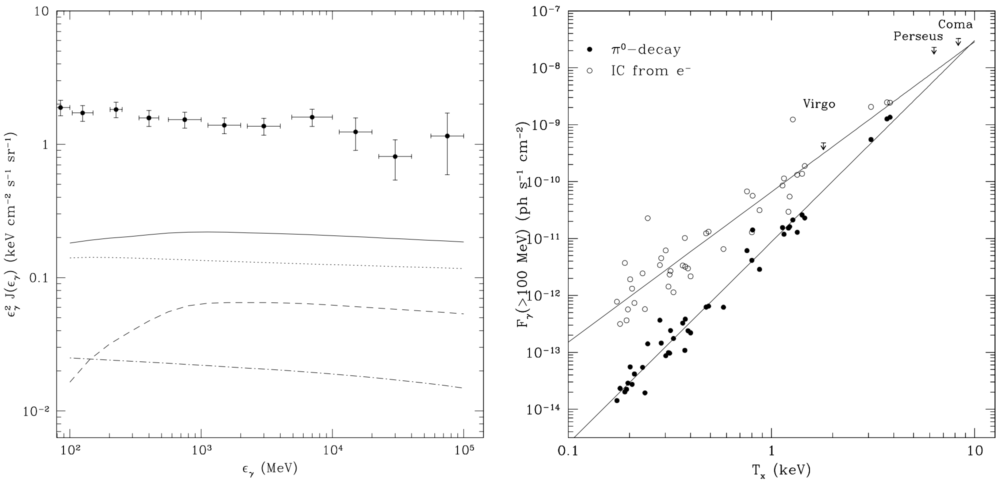

Fig. 5. *Left*: γ-ray background: data (points with errorbars) and model predictions (see text for details). *Right*: predicted cluster γ-ray luminosity versus cluster virial temperature. EGRET upper limits are from Reimer et al. (2003).

of order 30% and 10 % are produced by π^0-decay and IC emission from secondary $e^\pm$, respectively. All three components produce the same flat spectrum, a reflection of the fact that the CRs distributions were generated in strong shocks. The computed flux is only $\sim$ 15 % of the observed CGB by Sreekumar et al. (1998). It is difficult to imagine a higher contribution from π^0-decay and IC emission from $e^\pm$. In fact, if more CR protons were produced at shocks, CR-induced shock modifications would actually reduce the population of γ-ray emitting protons (and $e^\pm$). On the other hand, the fraction, η, of shock ram pressure converted into CR electrons, can be constrained by comparing the simulated clusters' γ-ray photon luminosity above 100 MeV to the upper limits set by the EGRET (Sreekumar et al. 1996; Reimer et al. 2003) for nearby GCs. This is done in Fig. 5 (right panel). The simulation data (open circles) are best-fit by the curve (solid line):

$$L_\gamma(> 100 \text{ MeV}) = 8.7 \times 10^{43} \times \left(\frac{\eta}{4\times 10^{-3}}\right) \left(\frac{T_x}{\text{keV}}\right)^{2.6} \text{ ph s}^{-1}. \quad (1)$$

Thus, the EGRET upper limits require that $\eta \leq 0.8\%$. This implies an upper limit on the computed γ-ray flux of about 0.35 keV cm^{-2} s^{-1} sr^{-1} or a fraction of order $\sim$ 25 % of the CGB. In view of the newly revised level of the CGB (Strong et al. 2003), this contribution would fill the gap between the observed flux and that which is already accounted for.

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